PHASED ARRAY COILS FOR HIGH RESOLUTION PROSTATE MR IMAGING

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Abstract – **MR imaging of the prostate can be greatly improved by using a phased array that combines the signals from individual receiver coils to form a composite image. Endourethral coils and a dual-coil endorectal probe were constructed and combined with a surface coil in a phased array system. Various phased array configurations were tested with *in vivo* canine experiments, which resulted in high-resolution images that clearly showed the anatomy of the prostate and surrounding structures such as the neurovascular bundles. The endourethral coils were useful in imaging the anterior portion of the prostate, while the endorectal coils provided high SNR in the posterior region of the prostate.**
Keywords – **prostate, MRI, phased array, endorectal coil, endourethral coil**

I. Introduction

Prostate cancer is the second leading cause of death in aging American men, with more than 50% of men over 80 years of age diagnosed with some form of the disease [1]. In light of the prevalence of this disease in such a large segment of the population, much work has been done to develop methods to help diagnose and treat prostate cancer. Examples of treatment options include traditional surgical resection, chemotherapy, and minimally invasive techniques, such as cryoablation, thermal ablation, and seed brachytherapy.

Many of these emerging technologies depend on an accurate image of the prostate during diagnosis (especially in needle biopsies), preoperative evaluation, and intraoperative image guidance. MRI has been identified as an ideal imaging modality for these purposes due to its excellent soft tissue contrast and higher resolution, compared to ultrasound and CT. Receiving coils are placed at or near the prostate to achieve higher resolution at smaller FOV; this usually is in the form of an endorectal coil, which is situated in the rectum in close proximity to the posterior floor of the prostate. Examples of endorectal coil use include needle biopsy guidance [2] and image guidance of prostate brachytheraphy in a 0.5 T MRI system [3].

Another way to improve prostate imaging is to combine multiple imaging coils into one phased array system, where the signals from individual antennas are incorporated into one composite image. In this way, the overall field of view is increased, while still preserving the local SNR of each coil element of the array. A few instances of phased array systems for prostate imaging exist in the literature; however, most of these are limited to two elements in the phased array. Examples include a double-coil quadrature surface array in a 3 T system [4], and an endorectal-surface coil system for preoperative evaluation of prostatectomy [5].

Here we attempt to extend the current state of the art in phased array prostate imaging by adding more elements to the array and by using different types of coils as elements. In particular, endourethral coils are employed to image the regions of the prostate surrounding the urethra. Endourethral coils are a relatively new technology never before used in prostate MRI, and are described more fully in the literature [6]. To validate our ideas, custom endorectal and endourethral imaging coils were constructed. Various combinations of endorectal coils, endourethral coils, and surface coils were investigated using the canine prostate as an experimental model.

II. Methods

Several antennas were constructed for use in prostate imaging. Two types of endourethral coil were implemented (loop and loopless), and a dual-coil endorectal probe was also constructed (Figure 1). To simulate the loaded conditions *in vivo*, the matching, detuning, and Q characteristics of each coil were verified using a network analyzer with the coils immersed in a tub of water (50 x 37 x 20 cm). In addition, several commercially available coils were evaluated for use in the phased array system: this included a standard cardiac surface coil, a pelvic surface coil, and an endorectal probe employing an inflatable balloon for stability (Medrad Inc., Indianola PA). In addition, a 16 Fr loop coil that was originally meant for endourethral use was instead used endorectally in one of the canine prostate studies. Various combinations of up to four imaging coils were connected to the input of a 1.5 T GE Signa scanner, which took the sum of the individual squared magnitudes to produce a composite image.

Fig. 1. The (a) dual-coil endorectal probe, (b) loopless endourethral coil, and (c) loop endourethral coil

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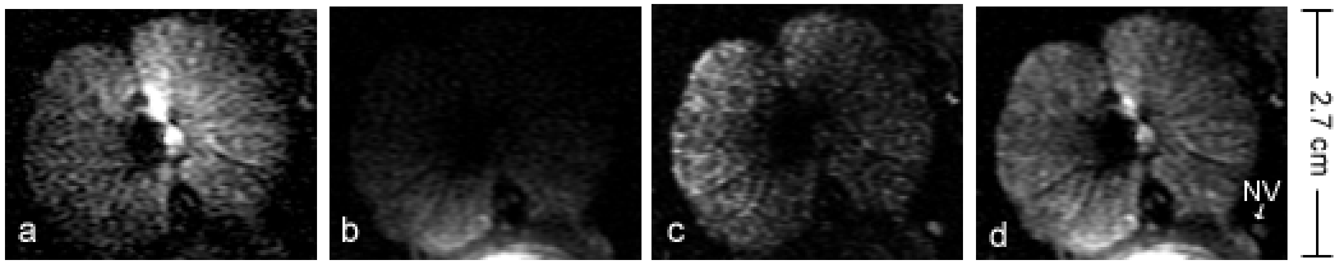

Fig. 2. Axial images of dog prostate for (a) loopless endourethral, (b) 16 Fr. endorectal coil, (c) surface pelvic coil, and (d) combined phased array system. Sequencing parameters: fat-saturated T2-weighted FSE; TR/TE = 4000/100 ms; NEX=8; FOV = 8 x 8 cm; matrix 256 x 256; slice thickness = 3 mm. Legend: NV = neurovascular bundle

A. Endourethral Coil Design

Loopless Design

A loopless coil consists of a coaxial inner conductor extending a quarter-wavelength away from the end of the grounded outer conductor, thus forming a dipole antenna. The loopless coil used in the experiment is encased in a polymeric sheath with an outer diameter of 2.5 mm. A small-diameter coaxial cable is used to convey the antenna's signal to a shielded box containing a matching and detuning circuit.

Matching is achieved by a standard impedance network consisting of nonmagnetic chip capacitors and wirewound inductors. Detuning of the coil during the transmit phase of the body coil is achieved through the use of a PIN diode. During RF transmission, the scanner triggers a DC bias voltage that switches on the PIN diode, which creates a resonant LC tank circuit that presents a very high impedance to the antenna. Thus, the antenna is decoupled until the transmit mode ends and the PIN diode is switched off, thereby preventing the coil from interfering with the excitation's flip angle. A balun was implemented in the matching/detuning box to eliminate shield currents. The balun consists of a coiled coaxial wire and a parallel capacitor connecting the network ground to the scanner ground. This resonant LC tank circuit was designed to "choke" any noise currents from the scanner ground.

Loop Design

The endourethral loop coil used in prostate imaging consists of a copper trace etched as a square loop on a piece of flexible polyimide film. This flexible circuit is ensheathed in polymer tubing that has an outer diameter of 5 mm, and is connected to the scanner inputs via a small-diameter coaxial cable.

Again, chip capacitors are used to match the antenna to the scanner, and a PIN diode is used for decoupling. However, these components are soldered directly onto the flex circuit itself, in order to preserve the antenna's high Q. A "bazooka balun" was constructed from a $\lambda/4$ length of copper braiding, with one end shorted to the coaxial ground.

B. Dual-coil Endorectal Probe Design

The endorectal imaging probe was constructed with two loop coils mounted close together to increase the effective field of view along the basolateral direction of the prostate, while preserving the high SNR of each coil. Each loop coil is exactly analogous in design to the endourethral loop coil described previously. Both loop coils were etched onto standard phenolic PCB board, one on each side and slightly overlapping each other. Each loop is 24 mm x 14 mm and rectangular in shape, while the entire circuit board (6.2 cm x 2.0 cm) is mounted on a tapered silicone probe head attached to a 24 cm plastic handle. The probe head was coated with a protective plastic and covered with a condom.

Reduction of crosstalk between the two loop coils was an important consideration in the probe design. The preferred solution to crosstalk reduction was to determine the optimal amount of overlap between the two coils so that the inward and outward flux exactly cancels. However, since the ideal amount of overlap was unknown prior to the coils being etched, strips of adhesive copper tape (3M) were applied onto one side of the board to block some of the interloop flux, thus decreasing the effective amount of coil overlap. The elimination of crosstalk was verified by ensuring that no artifact was seen when the endorectal coils were imaged in water by the scanner's body coil.

C. In Vivo Studies

The use of phased arrays was investigated with *in vivo* imaging studies of the canine prostate. These experiments were conducted in accordance with all regulations set forth by the relevant institutional and governmental agencies. The dogs were anesthetized prior to the procedure and placed supine on the scanner bed, caudal end first. Large-FOV scout images were acquired to help guide coil placement so that the most sensitive parts of the endourethral and endorectal coils were closest to the prostate. A variety of fast spin echo (FSE), T2-weighted imaging scans were then taken in the region of the prostate. The field of view in each case was kept small (8 cm) with encoding steps of 256 x 256; the resultant pixel size was 0.31 mm.

III. Results

A. In vivo studies

Various combinations of coils were used to implement the phased array system in each experiment. Figure 2 shows axial images produced by a phased array consisting of a loopless endourethral coil, a 16 Fr catheter loop coil in the rectum, and a pelvic surface coil. Figure 3 shows images of the prostate and rectum generated by the phased array consisting of the loopless endourethral coil and the dual-coil endorectal probe. The various layers of the rectal wall can be seen clearly from Figure 3b. It is important to note that Figures 3a and 3b are from the same acquired image but were separated into two images, so that the contrast levels for each could be adjusted separately. Phased arrays with the loop endourethral coil have not yet been implemented; however, a typical image produced by such a coil has been included for comparison (Figure 4). Insertion of this loop coil required surgery, since it was too large to fit through the canine urethra.

B. Coil performance

For the images shown in Figure 2, the matching of the endourethral loopless coil was adequate, with a reflection coefficient ρ of 0.3. Figure 2d shows the phased array's ability to image the neurovascular bundles near the posterior base of the prostate.

Performance of the dual-coil endorectal probe was generally excellent. The magnitude of reflection coefficients for both coils was less than 0.1 under loaded conditions in vivo. Elimination of crosstalk was achieved at the frequency of interest (crosstalk isolation = –30 dB at 63.9 MHz).

IV. Discussion

The images show that the dual-coil endorectal probe and the endourethral coils alone are able to produce high resolution images of the prostate and surrounding structures, with a resolution of at least 0.31 mm. The dual-coil endorectal probe maintained high SNR all along the posterior side of the prostate, and indeed was the dominant source of signal in the image. It was demonstrated that the neurovascular bundles near the base of the prostate can be clearly visualized; it is important to identify these structures to prevent any harm to them during interventions. The phased array system also allows good visualization of the rectal wall, which is helpful in determining the extracapsular spread of the prostate cancer. In turn, it was demonstrated that the loopless endourethral coil provided good coverage of the anterior portion of the prostate.

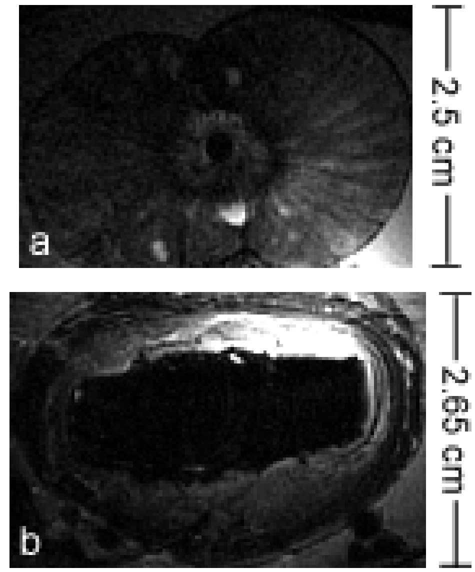

Fig. 3. Phased-array axial image of (a) prostate and (b) rectal wall, obtained by the phased array of the loopless endourethral coil and the dual-coil endorectal probe. The mucosa, submucosa, and muscle layers of the rectal wall can be seen clearly. Sequencing parameters: non-fat-saturated T2-weighted FSE; TR/TE = 4000/160 ms, NEX=8, FOV = 8 x 8 cm, matrix 256 x 256, slice thickness = 2 mm.

It would appear that a phased array of endorectal, endourethral, and surface coils is optimal for prostate imaging; in particular, the endorectal and endourethral coils generate high SNR in distinctly different anatomical regions of the prostate.

Figures 3a and 3b shows a current limitation of the phased array approach to MR imaging: the image had to be separated into two individual images, so that contrast could be adjusted separately to optimize visualization of detail in each region. Each region has a different range of signal intensities, so adjustment of contrast to elucidate features in one region may obscure another part of the image by making the pixels too dark or too bright. However, this limitation can be overcome by appropriate correction algorithms. If the location and orientation of each coil is known, a correction algorithm could renormalize the raw image data on the basis of *a priori* knowledge of each coil's field distribution. Such an algorithm needs to be investigated for use in real-time interventional settings.

One way to improve the phased array is to use a loop design for the endourethral coil rather than a loopless design. The benefit is that the SNR and Q of a loop coil are much higher than is achievable with loopless antennas. However, use of the endourethral loop coil is impractical for a canine model, since the dog urethra is smaller than the loop (at least 15 Fr), which therefore requires difficult surgical transection to achieve placement. Use of such a coil may be more feasible for human studies, where the urethra is much larger.

The endorectal probe can also be improved: a third coil can be added to further increase the effective field of view.

The results gleaned from the canine prostate model, while instructive, do not entirely mimic the situation in the human prostate. The canine prostate has none of the zonal anatomy that the human prostate possesses; distinction of these zones is important because it has been shown that cancer nodes are more likely to form in certain zones than others (the peripheral zone in particular). The dog prostate is typically smaller than the human prostate, especially when compared to the enlarged prostates that are commonly found in aging men. There were also no cancer nodes in the canine prostates that we examined, thus the phased array's ability to differentiate cancerous tissue could not be tested in these experiments. Human studies must be performed to validate the phased array's utility in detecting prostate cancer.

V. Conclusion

Early results suggest that a phased array system of endorectal coils, endourethral coils and surface coils produce high-resolution images of the prostate that are of very high quality. This capability to generate high resolution prostate images will become increasingly important as diagnosis and treatment options for prostate cancer continue to evolve.

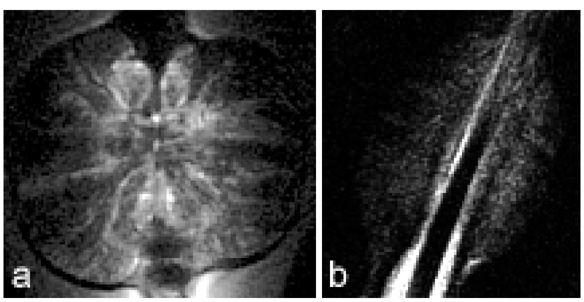

Fig. 4. Comparison of coronal images of dog prostate for (a) loop endourethral coil and (b) loopless endourethral coil.

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